

Observational evidences of the Yukawa Potential Interacting Dark Matter

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ABSTRACT

Recent observations in galaxies and clusters indicate dark matter density profiles exhibit core-like structures which contradict to the numerical simulation results of collisionless cold dark matter. On the other hand, it has been shown that cold dark matter particles interacting through a Yukawa potential could naturally explain the cores in dwarf galaxies. In this article, I use the Yukawa Potential interacting dark matter model to derive two simple scaling relations on the galactic and cluster scales respectively, which give excellent agreements with observations. Also, in our model, the masses of the force carrier and dark matter particle can be constrained by the observational data.

Subject headings: dark matter, galaxies, clusters

1. Introduction

The nature of dark matter remains a fundamental problem in astrophysics and cosmology. The rotation curves of galaxies and the derived mass profiles in clusters indicate the existence of dark matter. It is commonly believed that dark matter is collisionless and becomes non-relativistic after decoupling. Therefore, they are regarded as cold dark matter (CDM). The CDM model can provide excellent fits on large scale structure observations such as Ly α spectrum (Croft et al. 1999; Spergel and Steinhardt 2000), 2dF Galaxy Redshift Survey (Peacock et al. 2001) and Cosmic Microwave Background (Spergel et al. 2007).

However, N-body simulations based on the CDM theory predict that the density profile of the collisionless dark matter halo should be singular at the center ($\rho \sim r^{-1}$) (Navarro et al. 1997) while observations in dwarf galaxies give $\rho \sim r^{-0.29 \pm 0.07}$ (Oh et al. 2011; Loeb and Weiner

2011). On the cluster scale, observational data from gravitational lensing also show that cores exist in some clusters (Tyson et al. 1998; Newman et al. 2011). In particular, Sand et al. (2008) get $\alpha = -0.45 \pm 0.2$ by the combination of gravitational lensing and dynamical data of clusters MS2137-23 and Abell 383. Clearly, observations do not support the numerical small-scale predictions by the CDM model. This discrepancy is known as the core-cusp problem (de Blok 2010).

Many theories have been invoked to solve the core-cusp problem. For example, some baryonic processes such as supernova feedback have been suggested to alleviate the problem (Weinberg and Katz 2002; de Blok 2010). Recent high resolution cosmological hydrodynamical simulations show that cored dark matter density profile could be produced in Milky-Way like halo if there is enough radiation pressure of massive stars before they explode as supernovae (Maccio et al. 2011). However, it is still controversial to make the conclusion because the actual contribution of supernova explosions is limited by the low star formation efficiency (Peñarrubia et al. 2012). Also, it is challenging to invoke baryonic processes as the main mechanisms for some dark matter dominated galaxies (Vogelsberger et al. 2012). Another spectacular idea is that dark matter is not cold. The existence of keV sterile neutrinos, as a candidate of warm dark matter (WDM), has been proposed to solve the discrepancies (Bode et al. 2001; Xue and Wu 2001; Cho 2012). However, recent observations tend to reject the keV sterile neutrinos to be the major component of dark matter since the observational bound of sterile neutrino mass in Lyman-alpha forest contradicts to that in x-ray background (Abazajian and Koushiappas 2006; Viel et al. 2006; Seljak et al. 2006). Also, the WDM model alone cannot get a good agreement on the large scale power spectrum (Spergel and Steinhardt 2000; Boyarsky et al. 2009). Therefore, the success of the CDM model on large scales suggests that a modification of the dark matter properties may be the only approach to solve the discrepancies (Spergel and Steinhardt 2000). Spergel and Steinhardt (2000) proposed that the conflict of observations and simulations can be reconciled if the CDM particles are self-interacting. Later, Burkert (2000); Yoshida et al. (2000) performed numerical simulations of self-interacting dark matter (SIDM) with constant cross section and showed that core-like structures could be produced. However, this proposal fell out of favour because gravitational lensing and X-ray data indicate that the cores of clusters are dense and ellipsoidal where SIDM model predicts that to be shallow and spherical (Loeb and Weiner 2011). Also, there is a discrepancy on the required cross section per unit mass in dwarf galaxies ($\sigma/m \sim 0.1 - 1 \text{ cm}^2 \text{ g}^{-1}$) and clusters ($\sigma/m \sim 0.01 - 0.1 \text{ cm}^2 \text{ g}^{-1}$) (Miralda-Escudé 2002; Randall et al. 2008; Buckley and Fox 2009; Tulin et al. 2013). Recent numerical simulations indicate that only a small window open for a constant cross section SIDM model to work as a distinct alternative to CDM (Zavala et al. 2013). Therefore, a velocity-dependent cross section of the SIDM were explored to tackle the problems.

Loeb and Weiner (2011) proposed that the possible existence of a Yukawa potential among the dark matter particles can resolve the problem raised by the SIDM with constant cross section. The velocity dependence could make scattering important in dwarf galaxies but unimportant in clusters (Vogelsberger et al. 2012). In this model, the dark matter particles of mass m is set by an attractive Yukawa potential with coupling strength α mediated by a gauge boson of mass m_ϕ in the dark sector (Feng et al. 2010; Loeb and Weiner 2011). The cross section is well fitted by

$$\sigma \approx \begin{cases} \frac{4\pi}{m_\phi^2} \beta^2 \ln(1 + \beta^{-1}), & \beta \leq 0.1, \\ \frac{8\pi}{m_\phi^2} \beta^2 / (1 + 1.5\beta^{1.65}), & 0.1 \leq \beta \leq 10^3, \\ \frac{\pi}{m_\phi^2} (\ln \beta + 1 - 0.5 \ln^{-1} \beta)^2, & \beta \geq 10^3, \end{cases} \quad (1)$$

where $\beta = \pi v_{max}^2 / v^2 = 2\alpha m_\phi / (mv^2)$ and v is the relative velocity of the dark matter particles (Loeb and Weiner 2011). The v_{max} is the velocity at which σv reaches its maximum value. In the original proposal of the Yukawa interacting dark matter model, the parameter v_{max} was considered to be $v_{max} \sim 10 - 100$ km/s in order to match the characteristic velocities of dwarf galaxies and clusters so that the scattering rate is larger in dwarf galaxies but much smaller in clusters. Nevertheless, this is not a necessary range. In Fig. 1, we can see that the cross section per unit mass is still larger on the galactic scale ($v \sim 10 - 100$ km/s) even if $v_{max} \sim 10^4$ km/s. Also, the scattering rate of dark matter particle is $\rho_c(\sigma/m)v$, which is still larger in galaxies because the central density ρ_c is about 10 times larger than that in clusters. In this article, I release the free parameter v_{max} to $\sim 10^4$ km/s so that the cross section will be $\sigma \propto (\ln \beta + 1)^2$ and $\sigma \propto \beta^{-0.35}$ on the galactic ($\beta \geq 10^3$) and cluster scales ($\beta \sim 10^2$) respectively. Therefore, the cross section is more velocity dependent on the cluster scale. In the following, I will use the above velocity-dependent self-interacting dark matter (vdSIDM) model with $v_{max} \sim 10^4$ km/s to derive a scaling relation to relate the total mass of dark matter halo M and v . Then, I will compare the derived scaling relations with empirical fits on the galactic and cluster scales.

2. vdSIDM model in galaxies and clusters

In the vdSIDM model, the size of a core R_c in a structure depends on the self-interacting rate of dark matter particles. Inside the core, we may assume that the dark matter particles interact with each other at least once during the evolution of a galaxy or cluster. Therefore, at $r = R_c$, we have

$$\rho_c \left(\frac{\sigma}{m} \right) v \approx H_0, \quad (2)$$

where $\rho_c = 3M_c/4\pi R_c^3$ is the central density of the core, M_c is the total mass of the core and H_0 is the Hubble constant (Rocha et al. 2012). By using the Virial relation $v \approx \sqrt{GM_c/R_c}$ and Eq. (2), we get

$$M_c = \left(\frac{3}{4\pi} \right)^{1/2} \left(\frac{\sigma}{m} \right)^{1/2} H_0^{-1/2} G^{-3/2} v^{3.5}. \quad (3)$$

In galaxies, since the core mass is about one-tenth of the total mass ($M_c \sim 0.1M$) (Rocha et al. 2012), we have

$$\log \left(\frac{M}{M_\odot} \right) = 3.65 + 0.5 \log \left(\frac{\sigma/m}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right) + 3.5 \log \left(\frac{v}{1 \text{ km/s}} \right). \quad (4)$$

For $\beta \geq 10^3$, the cross section in Eq. (1) can also be approximated by using a powerlaw of v (see Fig. 2):

$$\log \left(\frac{\sigma}{m} \right) = -0.37 \log \left(\frac{v}{1 \text{ km s}^{-1}} \right) + \log \left(\frac{\sigma_0}{m} \right), \quad (5)$$

where σ_0 is a constant which depends on m_ϕ . By putting the above equation into Eq. (4), we get

$$\log \left(\frac{M}{M_\odot} \right) = 3.65 + 0.5 \log \left(\frac{\sigma_0/m}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right) + 3.3 \log \left(\frac{v}{1 \text{ km/s}} \right). \quad (6)$$

On the other hand, the empirical fit of the baryonic Faber-Jackson relation obtained from a representative sample of 436 galaxies is given by $\log(v/1 \text{ km s}^{-1}) = 0.299 \log(M_B/M_\odot) - 1.053$ (Catinella et al. 2012). Since $M_B \approx 0.17M$, the observed Faber-Jackson relation becomes $\log(M/M_\odot) = 4.29 + 3.34 \log(v/1 \text{ km s}^{-1})$. Compare the empirical fit with Eq. (6), we get $\sigma_0/m \approx 1.9 \text{ cm}^2 \text{ g}^{-1}$. By Eq. (5), the cross section per unit mass for dwarf galaxies ($v \sim 50 \text{ km/s}$) and Milky-Way size galaxies ($v \sim 200 \text{ km/s}$) are $\sigma/m \sim 0.4 \text{ cm}^2 \text{ g}^{-1}$ and $\sigma/m \sim 0.2 \text{ cm}^2 \text{ g}^{-1}$ respectively. Therefore, both the power-law dependence of the scaling relation (≈ 3.3) and the order of magnitude of the cross section per unit mass ($\sigma/m \sim 0.1 - 1 \text{ cm}^2 \text{ g}^{-1}$) are generally agree with the recent observations (Buckley and Fox 2009; Peter et al. 2012; Tulin et al. 2013). Furthermore, since $\beta \geq 10^3$ in galaxies, by using $\sigma_0/m \approx 1.9 \text{ cm}^2 \text{ g}^{-1}$ and Eq. (1), we have $m_\phi^2 m \approx \pi(\ln \beta + 1)^2/(\sigma/m) \sim 0.3 \text{ GeV}^3$. By combining the above result with the estimated lower bound derived from dwarf galaxies $m_\phi > 40 \text{ MeV}$ (Buckley and Fox 2009), we have $m \leq 200 \text{ GeV}$.

Similarly, we can apply the same model to clusters. However, since $v \sim 10^3 \text{ km/s}$ ($1 \ll \beta \leq 10^3$) in clusters, by Eq. (1), the cross section drops faster with velocity (see Fig. 1):

$$\frac{\sigma}{m} = \frac{8\pi}{m_\phi^2 m} \frac{\beta^2}{(1 + 1.5\beta^{1.65})} \approx \left(\frac{\sigma_0'}{m} \right) \left(\frac{v_{max}}{v} \right)^{0.7}. \quad (7)$$

By using the result $m_\phi^2 m \sim 0.3 \text{ GeV}^3$, we have $\sigma_0'/m = 0.012 \text{ cm}^2 \text{ g}^{-1}$. Therefore, the cross section per unit mass in clusters is $\sigma/m \sim 0.06 \text{ cm}^2 \text{ g}^{-1}$, which is consistent with

the recent observed bounds $\sigma/m \leq 0.1 \text{ cm}^2 \text{ g}^{-1}$ (Miralda-Escudé 2002; Randall et al. 2008; Buckley and Fox 2009; Peter et al. 2012; Tulin et al. 2013). Since the size of a cluster is about 100 times of the core size, which is equivalent to $M \sim 100M_c$ (Arabadjis et al. 2002; Rocha et al. 2012), by putting Eq. (7) into Eq. (3), we have

$$M = 100 \left(\frac{3}{4\pi} \right)^{1/2} H_0^{-1/2} G^{-3/2} v_{max}^{0.35} \left(\frac{\sigma_0}{m} \right)^{1/2} v^{3.15}. \quad (8)$$

Since $v \approx \sqrt{3kT/m_g}$, where T and m_g are the temperature and mean mass of a hot gas particle, we can obtain a scaling relation

$$M \approx 1.7 \times 10^{14} M_\odot \left(\frac{T}{2 \text{ keV}} \right)^{1.58}. \quad (9)$$

Surprisingly, this derived scaling relation gives excellent agreements with both the power dependence and proportionality constant of the empirical fits from 118 clusters $M = (1.56 \pm 0.01) \times 10^{14} M_\odot (T/2 \text{ keV})^{1.57 \pm 0.06}$ (Ventimiglia et al. 2012).

3. Discussion

The original purpose of suggesting the vdSIDM model is to explain the observed cores in dwarf galaxies without affecting the dynamics in clusters (Loeb and Weiner 2011). They assume $v_{max} \sim 10 - 100 \text{ km/s}$ so that the maximum cross section lies on the galactic scale (Vogelsberger et al. 2012). In fact, this is a free parameter which depends on m_ϕ and m , and it is not necessary to be about 10-100 km/s. Rocha et al. (2012) show that $\rho_c \sim 0.015 M_\odot \text{ pc}^{-3} (v/100 \text{ km s}^{-1})^{-0.55}$ by simulations, which means the central density of dark matter is higher in dwarf galaxies. As a result, the scattering rate of dark matter particle $\sim \rho_c (\sigma/m) v$ is always larger in dwarf galaxies than clusters even if $v_{max} \sim 10^4 \text{ km/s}$. On the other hand, the circular velocity of a dwarf galaxy can be obtained by substituting Eq. (5) into Eq. (2), which gives $v \approx (4\pi G H_0/3)^{0.38} R^{0.76} (\sigma_0/m)^{-0.38}$. For $R = 250 \text{ pc}$ and $R = 500 \text{ pc}$, we get $v = 13 \text{ km/s}$ and $v = 22 \text{ km/s}$ respectively. These values are consistent with the observed circular velocities on the dwarf spheroidal scale (Walker et al. 2009; Wolf et al. 2010). Therefore, the large v_{max} can still solve the too big to fail problem suggested by Boylan-Kolchin et al. (2011); Vogelsberger et al. (2012).

In this article, I show that if $v_{max} \sim 10^4 \text{ km/s}$, the cross section goes like $\sim v^{-0.37}$ and $\sim v^{-0.7}$ in galactic and cluster scales respectively. The derived scaling relation on the galactic scale is $M \propto v^{3.3}$, which agrees with observations $M \propto v^{3.34}$ (Catinella et al. 2012). The cross section per unit mass contrained by this model is $\sigma/m \sim 0.2 - 0.4 \text{ cm}^2 \text{ g}^{-1}$ for $v =$

50–200 km/s, which is also consistent with the observed bounds in dwarf and normal galaxies (Buckley and Fox 2009; Peter et al. 2012; Tulin et al. 2013). By applying the same model in clusters, we get $M \propto T^{1.58}$, which again gives excellent agreements with observations in both proportionality constant ($\sim 10^{14} M_\odot$) and power dependence (1.57 ± 0.06) (Ventimiglia et al. 2012). These results provide evidences on the non-power-law velocity dependent cross section of self-interacting dark matter. If v_{max} is 10–100 km/s, the derived scaling relations would be $M \propto v^{3.15}$ and $M \propto T^{0.75}$ on the galactic and cluster scales respectively. Obviously, they do not match the empirical fits from observational data. Furthermore, in my model, it predicts $m_\phi^2 m \sim 0.3 \text{ GeV}^3$. If $m_\phi \geq 40 \text{ MeV}$, then $m \leq 200 \text{ GeV}$, which is a testable range in the future large hadron collision experiments.

Recently, Vogelsberger and Zavala (2013) study the impact of self-interacting dark matter on the velocity distribution of dark matter haloes and the anticipated direct detection signals. They find that all SIDM and vdSIDM models show departure from the velocity distribution of the CDM model in the center of the Milky Way halo. Therefore, different SIDM scenarios, including my model, might be distinguished from each other through the details of direct detection signals in the future (Vogelsberger and Zavala 2013).

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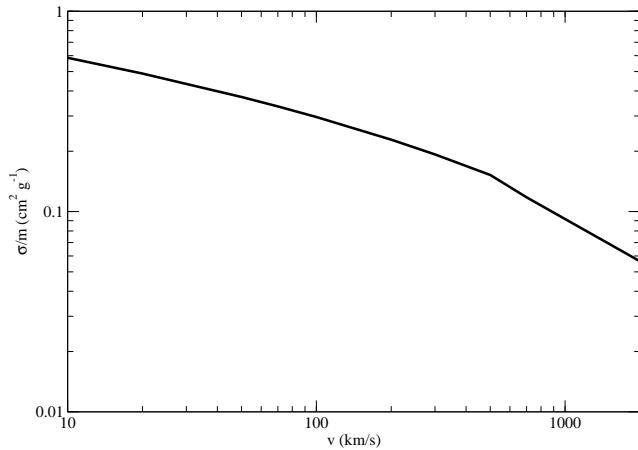


Fig. 1.— σ/m versus v for $v = 50 - 1000$ km/s, $v_{max} = 10^4$ km/s and $m_\phi^2 m = 0.3$ GeV³.

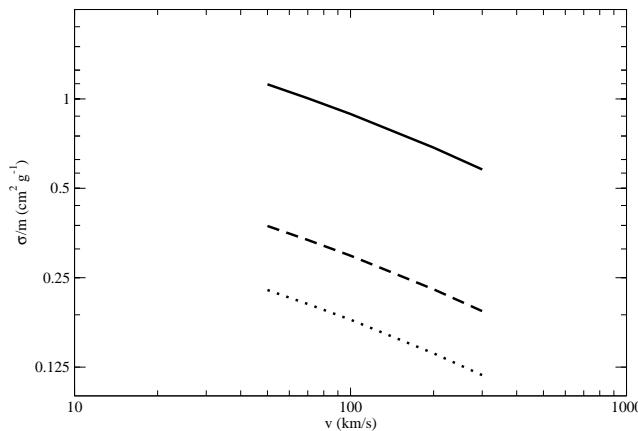


Fig. 2.— The solid line, dashed line and dotted line represent σ/m versus v for $m_\phi^2 m = 0.1$ GeV³, 0.3 GeV³ and 0.5 GeV³ respectively. The slopes of the lines are all -0.37 .

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